^{26}Al AND ^{10}Be ACTIVITIES IN CHELYABINSK (LL5): IMPLICATIONS FOR COSMIC-RAY EXPOSURE HISTORY.

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Introduction: The fall of Chelyabinsk (LL5) in 2013 was spectacular, cautionary, and well documented [1]. The availability of samples offers a rare opportunity to construct a cosmic-ray exposure constrained by direct observations related to the meteoroid's size and recent orbital history. Towards this end, we report ^{26}Al and ^{10}Be activities of up to 10 Chelyabinsk (LL5) samples

Experimental methods: The samples analyzed were chips (57-110 mg) taken from the same specimens analyzed for noble gases [1,2] and/or Sm isotopes [3]. Samples were dissolved in a 4:1 (vol:vol) mixture of conc. HF and conc. HNO_3. Be and Al were separated and prepared for accelerator mass spectrometry (AMS) at Purdue University as described by [4].

Results: Results are shown in Table 1. Unusually high Mg contamination was observed in some Al samples prepared for AMS, leading to larger uncertainties of the ^{26}Al activities of HR-4 and HR-9.

The activities of both ^{26}Al and ^{10}Be vary by 1-to-2 orders of magnitude, but are well correlated (Figure 1). They also correlate well with the independently measured concentrations of ^{3}He ($R^2 \geq 0.99$; Figure 1).

Discussion: We begin constructing a cosmic-ray exposure (CRE) history with the simplest hypothesis, a one-stage irradiation model and then comment on samples that do not fit the mold.

Meteoroid size: The size of Chelyabinsk has been estimated to be 9-10 m in radius, *r* [5], which corresponds to a mass of 10^{10} kg (density=3.5 g/cm^3) The mass collected to date amounts to only 10^3 kg.

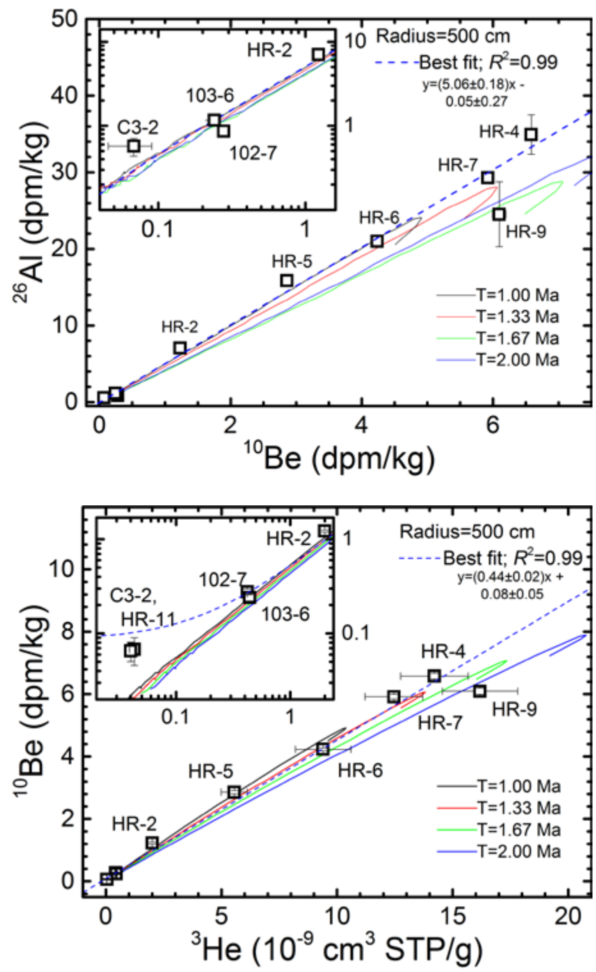
In a one-stage history, the Chelyabinsk meteoroid must have been large enough to accommodate all the concentrations measured for the cosmogenic nuclides.

Table 1. Activities and inferred sample depths, *d*.

ID	^{26}Al	^{10}Be	d_{26}	d_{10}
	dpm/kg		cm	
102-7	0.87±0.13	0.28±0.02	224	206
103-6	1.16±0.12	0.24±0.02	208	210
C3-2	0.57±0.14	0.07±0.02	240	274
HR-02	7.0±0.2	1.23±0.03	112	124
HR-04	34.9±2.6	6.58±0.09	--	--
HR-05	15.9±0.4	2.86±0.06	64	74
HR-06	21.0±0.4	4.23±0.05	46	51
HR-07	29.3±0.6	5.92±0.08	16	4 or 20
HR-09	24.5±4.2	6.10±0.10	3 or 34	9 or 14
HR-11		0.07±0.02		274

^{10}Be and ^{26}Al concentrations vary by factors of 97±32 and 61±15, respectively; the spreads are even larger for cosmogenic ^{3}He (>400), ^{21}Ne (>400), and ^{38}Ar (300), but may be influenced by gas losses or prior irradiation. The ranges of variation, factors of ~40, modeled by [6] for a spherical meteoroid with a radius of 3 m are smaller. We conclude that the radius of Chelyabinsk was at least 4 m and regard 3 m as a firm lower limit.

Figure 1. ^{26}Al, ^{10}Be, and ^{3}He measurements compared to modeling calculations (lines) of [6] for a body with a radius of 5 m and various assumed CRE ages. Modeled concentrations decrease from maxima at depths of ~15 cm to slightly lower values at the surface and to much lower values at depth of 5 m.



As radius increases, the maximum possible production rates decrease. For example, for $r \geq 5$ m, modeling gives $P_{26,max} \leq 38.5$ dpm/kg and $P_{10,max} \leq 12.5$ dpm/kg. With these maximum production rates and reasonable CRE ages (see below) it is difficult to reproduce the highest measured ^{10}Be and ^{26}Al activities. Thus either the mass calculations from fall phenomena measurements are too high, the measured activities are too high, the modeling results are too low, or the irradiation was complex.

Cosmic ray exposure (CRE) age, T: Several one-stage CRE ages have been presented: ~1.5 Ma ($^{36}Cl/^{10}Be$; [7]); ~1.2 Ma ($^{36}Cl/^{21}Ne$, [8]) and < 5 Ma (^{81}Kr; [8]); and 1.2 Ma (^{21}Ne in HR-7; [2]). The most precise of them places the T in a range comparable to the half-lives of both ^{26}Al (0.7 Ma) and ^{10}Be (1.38 Ma), implying that neither isotope reached its limiting (saturation) value. Under these conditions, we use the equation

$$\frac{^{10}\mathrm{Be}}{^{26}\mathrm{Al}} = \left(\frac{P_{10}}{P_{26}}\right)_{r,d} \frac{\left(1-e^{-\lambda_{10}T}\right)}{\left(1-e^{-\lambda_{26}T}\right)}$$

to calculate T for Chelyabinsk. P denotes a production rate either modeled for a sphere with radius r at a depth d, or empirical. From the slope of the best fit line of Figure 1 and ignoring the small intercept, we obtain $^{10}Be/^{26}Al = 0.20 \pm 0.01$. Empirical values of P_{10}/P_{26} are available for two large L or LL chondrites, namely, Gold Basin (R=3 to 5 m, N=15; [9]) and QUE 90201 (R=1.5 m, N=13; [10]), which give $P_{10}/P_{26} = 0.30$ and 0.31, respectively. Ratios from [6] are comparable at 0.33, and vary little with depth. With $P_{10}/P_{26} = 0.31$ we obtain $0.9 \leq T(Ma) \leq 1.4$ Ma for $0.19 \leq {^{10}Be}/{^{26}Al} \leq 0.21$ and a single best estimate of $T_{26/10} = 1.2 \pm 0.3$ Ma (N=7; σ_{mean}) or $T_{26/10} = 1.03 \pm 0.14$ Ma (N=5) excluding the extreme ages of HR-2 and HR-9. Similar calculations using the $^{3}He/^{10}Be$ ratios (Figure 1, lower panel) and a modeled value of P_3/P_{10}=0.745 (10^{-9} cm^3 STP g^{-1} Ma^{-1}/(dpm/kg), r=5 m; [6]) yield average ages of 1.38±0.27 (N=7) or 1.34±0.16 excluding HR-2 and HR-9. Because of the larger uncertainties associated with some ^{26}Al measurements and the high sensitivity of $T_{26/10}$ to small differences in the $^{10}Be/^{26}Al$ ratio, at this time we prefer the $^{3}He/^{10}Be$ CRE age of 1.34 Ma.

CRE ages may also be calculated from ^{21}Ne (or ^{38}Ar. Correlations of ^{21}Ne with ^{26}Al (R^2=0.44) and of ^{10}Be (R^2=0.76), however, are poorer with HR-4, 5, and 6 as noticeable outliers.

Noting that Itokawa, Chelyabinsk, and Appley Bridge have CRE ages that are similar and unusually short for material with LL-chondrite composition, Meier et al. [11] suggested that a single collision produced all three objects. Orbital data are permissive if not strongly supportive of this hypothesis [12]. Textures and the Ar/Ar systematics of the three objects differ and the apparent CRE age of Itokawa may reflect erosion. If, nonetheless, the hypothesis of [11] is correct then the LL precursor was a very complex body.

Sample depths: By using the model calculations of [6] for P_{26} and P_{10} and assuming a CRE age of 1.34 Ma, we can assign depths to the samples (Table 1).

Outliers: Figure 1 shows a tension between matching simultaneously the measured cosmogenic nuclide ratios (slopes of best-fit lines), and the high activities measured for some samples, which constrain the meteoroid's size. Nyquist et al. [3] argue that the high $^{3}He/^{21}Ne$ and $^{22}Ne/^{21}Ne$ ratios and high cosmogenic nuclide concentrations of HR-9 require the higher production rates characteristic of smaller meteoroids, r<1 m or perhaps of unusual exposure geometries.

HR-5 presents a different kind of problem. While intermediate concentrations of ^{26}Al, ^{10}Be, and ^{3}He appear mutually consistent, the cosmogenic ^{21}Ne and ^{38}Ar concentrations are the largest reported for any Chelyabinsk sample and imply a CRE age of ≥1.8 Ma for r=5 m. Furthermore, by standard measures the $^{3}He/^{21}Ne$ ratio of HR-5 is at least 3 times lower than expected. A two-stage history involving a long irradiation at great depth followed by recent excavation and ^{3}He loss is a possibility, although the ^{4}He concentration of HR-5 does not appear to be unusually low.

The ^{3}He, ^{21}Ne, and ^{38}Ar concentrations of C3-2 scatter but are ~10× lower than those of the two samples closest in shielding depth, namely, 102-7 and 103-6. ^{26}Al and ^{10}Be activities, in contrast, are only 2-4× lower.

Conclusions: Modeling of Chelyabinsk as an object 5-m in radius irradiated in one stage for 1.3 to 1.4 Ma adequately reproduces measurements of ^{26}Al, ^{10}Be, and ^{3}He, for 10 samples. Inconsistencies with results for $^{22}Ne/^{21}Ne$, ^{21}Ne, and ^{38}Ar for HR-5 and HR-9 may require a complex CRE history.

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